

MULTIPLE-THRESHOLD MULTIDIRECTIONAL INERTIAL DEVICE

BACKGROUND OF THE INVENTION

Field of the Invention

The present invention relates to a multiple-threshold multidirectional
5 inertial device.

Description of the Related Art

Multidirectional inertial devices (inertial switches) are known, which
detect the accelerations due to forces acting in at least two independent directions
and supply a recognition signal when the components of a force according to one
10 of these independent directions exceeds a pre-determined threshold. In particular,
inertial devices based upon MEMS (Micro-Electro-Mechanical System) inertial
sensors are currently available; advantageously, MEMS inertial sensors have high
sensitivity, contained overall dimensions and, above all, virtually negligible
consumption.

15 As is known, a MEMS inertial sensor comprises a fixed body and a
moving element, connected to one another by elastic suspension elements, which
enable a relative movement of the moving element with respect to the fixed body
according to pre-determined degrees of freedom, either rotational or translational.
Consequently, a force acting on the inertial sensor (or, equivalently, the
20 acceleration due to the application of said force) causes a displacement of the
moving element with respect to the fixed body in accordance with the degrees of
freedom allowed by the elastic suspension elements. Furthermore, respective
preferential detection axes of the inertial sensor correspond to such degrees of
freedom: in practice, the displacement of the moving element with respect to the
25 fixed body is maximum when the direction of a force (or of a moment, in the case

of rotational sensors) acting on the sensor is parallel to a preferential detection axis.

Normally, a multidirectional inertial device comprises a MEMS inertial sensor having at least two degrees of translational freedom (and thus two preferential detection axes), or else at least two sensors having a translational degree of freedom and respective preferential detection axes that do not coincide and are preferably orthogonal to one another. As mentioned previously, a recognition pulse is generated whenever the component of an acceleration along one of the preferential detection axes exceeds a pre-set threshold. Furthermore, the threshold is preferably the same for all the axes.

Known inertial devices suffer, however, from some limitations. It is in fact evident that a force or, equivalently, the acceleration caused by this force, albeit having an intensity higher than the pre-determined threshold, may fail to be detected if its direction shifts away significantly from the preferential detection axes. In this case, the components of this acceleration along the preferential detection axes may be less than the pre-set threshold.

For reasons of greater clarity, reference is made to Figure 1, which shows a first preferential detection axis X and a second preferential detection axis Y of a bi-directional inertial device, herein not illustrated, comprising for example two linear MEMS inertial sensors (*i.e.*, having one translational degree of freedom); for both of the preferential detection axes a same threshold S is fixed. Figure 1 moreover shows an acceleration, which has a magnitude A greater than the threshold S and forms an angle α with the first preferential detection axis X. The components of the acceleration along the preferential detection axes, herein designated by A_X , A_Y , are equal to:

$$A_X = A \cos \alpha$$

$$A_Y = A \cos (90^\circ - \alpha)$$

In the worst case, to which Figure 1 refers, the angle α is 45° , so that we have:

$$A_x = A_y = A / \sqrt{2}$$

It is thus evident that the acceleration is not detected if:

5
$$A < S / \sqrt{2} = S \cdot 1.41$$

In other words, the detection of a direct acceleration can fail even if the magnitude of the acceleration is considerably greater than the threshold S.

On the other hand, in a large number of cases the mere lowering of the threshold S is not satisfactory, since even disturbance of modest intensity
10 would be detected, too. Furthermore, reconstruction of the exact value of the acceleration by analogical processing of the signals provided by the inertial sensors would not be acceptable, because it would entail so high a power consumption as to nullify the saving achieved due to the use of MEMS inertial sensors.

15 BRIEF SUMMARY OF THE INVENTION

An embodiment of the present invention overcomes the limitations described by improving the detection of the forces and/or of the accelerations to which the inertial device is subjected.

According to the present invention a multiple-threshold
20 multidirectional inertial device is provided, .

BRIEF DESCRIPTION OF THE DRAWINGS

For a better understanding of the invention, an embodiment thereof is now described, purely by way of non-limiting example and with reference to the attached drawings, in which:

25 Figure 1 illustrates graphs corresponding to quantities present in a known inertial device;

Figure 2 is a schematic top plan view of a known inertial sensor; and
Figure 3 illustrates a simplified block diagram corresponding to an
inertial device according to the present invention;

Figure 4 illustrates graphs corresponding to quantities present in the
5 inertial device of Figure 3; and

Figure 5 shows a partially sectioned top plan view of a portable
electronic apparatus incorporating the inertial device of Figure 3.

DETAILED DESCRIPTION OF THE INVENTION

Figure 2 illustrates, for reasons of clarity, an inertial sensor 1, of a
10 known type, having a preferential detection axis A. In detail, the inertial sensor 1
comprises a stator 2 and a moving element 3, connected to one another by means
of springs 4 in such a way that the moving element 3 is able to translate parallel to
the first preferential detection axis A.

The stator 2 and the moving element 3 are provided with a plurality of
15 first and second stator electrodes 5', 5'' and, respectively, with a plurality of mobile
electrodes 6. Each mobile electrode 6 is positioned between two respective stator
electrodes 5', 5'', which it partially faces; consequently, each mobile electrode 6
forms, with the two adjacent fixed electrodes 5', 5'', first and, , second capacitors,
with plane and parallel faces, respectively. Furthermore, all the first stator
20 electrodes 5' are connected to a first stator terminal 1a, and all the second stator
electrodes 5'' are connected to a second stator terminal 1b, while the mobile
electrodes 6 are grounded. Consequently, from the electrical point of view, the
inertial sensor 1 can be idealized as a first equivalent capacitor 8 and a second
equivalent capacitor 9 (illustrated herein with dashed lines), having first terminals
25 connected to the first stator terminal 1a and, respectively, to the second stator
terminal 1b, and second terminals connected to ground. Furthermore, the first
equivalent capacitor 8 and the second equivalent capacitor 9 have variable
capacitances correlated to the relative position of the moving element 3 with

respect to the rotor 2; in particular, the capacitances of the equivalent capacitors 8, 9 at rest are equal and are unbalanced in the presence of an acceleration oriented according to the preferential detection axis (in this case, the first axis X).

According to what is illustrated in Figure 3, a multidirectional inertial device according to an embodiment of the present invention, designated as a whole by the reference number 10, comprises a first inertial sensor 11 and a second inertial sensor 12, coupled to a first transduction stage 14 and, respectively, to a second transduction stage 15, and a comparison stage 16.

The inertial sensors 11, 12 are linear sensors with capacitive unbalancing, which are made using MEMS technology and are of the type described previously with reference to Figure 1. In particular, the first inertial sensor 11 and the second inertial sensor 12 have a first preferential detection axis X and, respectively, a second preferential detection axis Y, which are perpendicular to one another and form preferential detection axes of the inertial device 10.

Each of the transduction stages 14, 15 comprises a current to voltage (C-V) converter 17, a filter 18, a subtractor node 19, and a rectifier 20.

In greater detail, the C-V converter 17 of the first transduction stage 14, which is in itself known, is based upon a differential charge-integrator circuit and has inputs connected to the first stator terminal 11a and to the second stator terminal 11b of the first inertial sensor 11. In practice, the C-V converter 17 of the first transduction stage 14 reads the capacitive unbalancing ΔC_X of the first inertial sensor 11 and supplies at one of its outputs 17a a first acceleration signal A_X , correlated to the component of an acceleration A, which is directed along the first preferential detection axis X and is due to forces acting on the first inertial sensor 11 (see also Figure 4). The output 17a of the C-V converter 17 is moreover connected to a non-inverting input of the subtractor node 19.

The filter 18, which is of a low-pass type, is connected between the output 17a of the C-V converter 17 and an inverting input 19a of the subtractor

node 19. In practice, the filter 18 extracts the continuous component of the first acceleration signal A_X and supplies at its output a first static-acceleration signal A_{XS} , exclusively correlated to the accelerations which are oriented according to the first preferential reference axis X, and are due to constant forces, such as the force of gravity.

The subtractor node 19 has an output, which is connected to the rectifier 20 and supplies a first dynamic-acceleration signal A_{XD} , exclusively correlated to the accelerations which are oriented along the first preferential reference axis X and are due to variable forces. In practice, the subtractor node 19 determines the first dynamic-acceleration signal A_{XD} , by subtracting the first static-acceleration signal A_{XS} from the first acceleration signal A_X .

The rectifier 20 is connected between the output of the adder node 19 and the comparison stage 16; moreover, an output of the rectifier 20 forms an output 14a of the first transduction stage 14 and supplies the absolute value $|A_{XD}|$ of the first dynamic-acceleration signal A_{XD} .

In the second transduction stage 15, the C-V converter 17, the filter 18, the subtractor node 19, and the rectifier 20 are connected to one another, as described above concerning the first transduction stage 14.

Furthermore, the C-V converter 17 of the second transduction stage 15 has inputs connected to the first stator terminal 12a and to the second stator terminal 12b of the second inertial sensor 12. In practice, the C-V converter 17 of the second transduction stage 15 reads the capacitive unbalancing ΔC_Y of the second inertial sensor 12 and supplies on its output 17a a second acceleration signal A_Y , correlated to the component of an acceleration A, which is parallel to the second preferential detection axis Y and is due to the forces acting on the first inertial sensor 11 (Figure 4). Furthermore, the filter 18 and the subtractor node 19 supply a second static-acceleration signal A_{YS} and, respectively, a second dynamic-acceleration signal A_{YD} , correlated to the accelerations which are oriented parallel to the second preferential detection axis Y and are due to the constant

forces and variable forces, respectively, acting on the second inertial sensor 12. The rectifier 20, the output of which forms an output 20b of the second transduction stage 15, supplies the absolute value $|A_{YD}|$ of the first dynamic-acceleration signal A_{YD} .

5 The comparison stage 16 comprises a first upper-threshold comparator 21, a second upper-threshold comparator 22, a first lower-threshold comparator 23, a second lower-threshold comparator 24, and an output logic circuit 27, having an AND gate 29 and a three-input OR gate 30.

 In detail, the first upper-threshold comparator 21 and the first lower-
10 threshold comparator 23 have respective inputs connected to the output 14a of the first transduction stage 14 and therefore receive the absolute value $|A_{XD}|$ of the first dynamic-acceleration signal A_{XD} . The second upper-threshold comparator 22 and the second lower-threshold comparator 24 have, instead, respective inputs connected to the output 15a of the second transduction stage 15, so as to receive
15 the absolute value $|A_{YD}|$ of the second dynamic-acceleration signal A_{YD} . Furthermore, the first and the second upper-threshold comparators 21, 22 have outputs connected to a first input 30a and to a second input 30b, respectively, of the OR gate 30, while the first and the second lower-threshold comparators 23, 24 have outputs connected to a first input 29a and to a second input 29b,
20 respectively, of the AND gate 29; the output of the AND gate 29 is connected to a third input 30c of the OR gate 30, and the output of the OR gate 30 forms an output 10a of the inertial device 10 and supplies a recognition signal R.

 The first upper-threshold comparator 21 and the first lower-threshold comparator 23 supply at output a first threshold-exceeding signal SX_H and a
25 second threshold-exceeding signal SX_L , respectively. In particular, the first and the second threshold-exceeding signals SX_H , SX_L are set at a first logic value (high), when the absolute value $|A_{XD}|$ of the first dynamic-acceleration signal A_{XD} is greater than a first upper threshold X_H and, respectively, than a first lower

threshold X_L , that is lower than the first upper threshold X_H (see also Figure 4), and are set at a second logic value (low) otherwise.

The second upper-threshold comparator 22 and the second lower-threshold comparator 24 supply at output, respectively, a third threshold-exceeding signal SY_H and a fourth threshold-exceeding signal SY_L . The third and fourth threshold-exceeding signals SY_H , SY_L are set at the first logic value (high), when the absolute value $|A_{YD}|$ of the second dynamic-acceleration signal A_{YD} is higher than a second upper threshold Y_H , and, respectively, a second lower threshold Y_L , lower than the second upper threshold Y_H , and are set at the second logic value (low) otherwise.

Hence, the output logic circuit 27 implements the following combinatorial function:

$$R = SX_H \text{ OR } SY_H \text{ OR } (SX_L \text{ AND } SY_L).$$

In practice, the recognition signal is set at the first logic value (high) when at least one of the following conditions is verified:

- the absolute value $|A_{XD}|$ of the first dynamic-acceleration signal A_{XD} is greater than the first upper threshold X_H ;
- the absolute value $|A_{YD}|$ of the second dynamic-acceleration signal A_{YD} is greater than the second upper threshold Y_H ; and
- the absolute value $|A_{XD}|$ of the first dynamic-acceleration signal A_{XD} and the absolute value $|A_{YD}|$ of the second dynamic-acceleration signal A_{YD} are greater than the first lower threshold X_L and, respectively, the second lower threshold Y_L .

Otherwise, the recognition signal R is set at the second logic value (low).

Consequently, the detection of an acceleration due to a force acting on the inertial device 10 is associated to the first logic value of the recognition signal R .

In the preferred embodiment described (Figure 4), the first and second thresholds X_H , Y_H are equal to one another and the first and the second lower threshold X_L , Y_L are equal to one another; moreover, the ratio between the upper threshold X_H and the first lower threshold X_L , and the ratio between the second upper threshold X_H and the second lower threshold Y_L are substantially equal to $1/\sqrt{2}$. The first and the second upper thresholds X_H , Y_H represent the minimum absolute value that an acceleration must have to be detected when it is parallel to the first preferential detection axis X or to the second preferential detection axis Y.

In practice, the dynamic components of acceleration along each of the preferential detection axes X, Y are compared with a respective upper threshold (X_H , Y_H) and a respective lower threshold (X_L , Y_L). If in at least one of the two cases the upper threshold is exceeded, the inertial device 10 detects in any case an acceleration and hence the action of a force; otherwise, acceleration is detected if the components which are parallel to the preferential detection axes X, Y are simultaneously greater than the respective lower thresholds.

In the preferred embodiment described, in particular, an acceleration A (Figure 4) which forms an angle of 45° with the preferential detection axes X, Y and has an absolute value higher than the first and the second upper thresholds X_H , Y_H is always detected, whereas an acceleration having an absolute value smaller than the first and the second lower thresholds X_L , Y_L is never detected. Furthermore, the maximum possible error (*i.e.*, whereby the maximum absolute value such that the detection may fail) is verified in the presence of the accelerations A', A'' of Figure 4. In the case of the acceleration A', if $|A_{ERR}|$ designates the maximum error possible, we have:

$$|A_{ERR}| = \sqrt{X_L^2 + Y_H^2} = \sqrt{X_L^2 + X_H^2} = \sqrt{(X_H / \sqrt{2})^2 + X_H^2}$$

$$|A_{ERR}| = X_H \sqrt{3/2} = 1.22 \cdot X_H$$

As is clear from the above description, the inertial device advantageously enables the efficiency of detection of the accelerations to be improved and the maximum error that might be committed to be reduced considerably. Thanks to the use of two thresholds for each preferential detection axis, it is in fact possible to detect accelerations with directions significantly different from the preferential detection axes, even when none of the upper thresholds is reached.

The inertial device described herein is moreover particularly suitable for being used as a device for reactivation from stand-by in portable electronic apparatus, such as cell phones or palm-top computers. To minimize consumption and thus increase autonomy, these types of apparatus in fact go into stand-by after a period of inactivity. With reference to Figure 5, a portable electronic apparatus 30 (here a cell phone) incorporating the inertial device 10 according to the invention can be automatically brought back into the active state as soon as a movement is detected, *i.e.*, when the recognition signal R is brought to the first logic value (for example, when the apparatus is picked up by a user). Advantageously, the dynamic-acceleration signals A_{XD} , A_{YD} provided by the transduction stages 14, 15 of the inertial device 10 are correlated only to the accelerations due to variable forces and, in practice, are different from zero only when the apparatus 30 is moved, in particular when it is picked up to be used. Note that, since the apparatus 30 may be variously oriented both during use and when it is not in use, not necessarily the components of the force of gravity along the preferential detection axes X, Y are always constant and they can be non-zero even when the apparatus 30 is not moved. However, as long as the apparatus 30 remains at rest, the force of gravity provides constant contributions to the acceleration signals A_X , A_Y , but zero contribution to the dynamic acceleration signals A_{XD} , A_{YD} . When, instead, the apparatus 30 is moved, also the force of gravity can advantageously provide a contribution to the dynamic-acceleration signals A_{XD} , A_{YD} , since the orientation of the preferential detection axes X, Y can

vary with respect to the vertical direction (*i.e.*, with respect to the direction of the force of gravity). Consequently, the movement due to the intervention of the user is more readily detected.

Furthermore, the use of MEMS-type inertial sensors, which are
5 extremely sensitive, have small overall dimensions, can be built at relatively low costs, and above all have virtually negligible levels of consumption, is particularly advantageous.

Finally, it is clear that modifications and variations can be made to the device described herein, without thereby departing from the scope of the
10 present invention.

In particular, the activation device 10 could have a third preferential detection axis, not parallel to and preferably orthogonal to the first two axes, and could comprise an inertial sensor and a transduction stage to detect the accelerations parallel to this third axis. Furthermore, a single inertial sensor with
15 more than one degree of freedom can be used, instead of a plurality of inertial sensors with a single degree of freedom.

It is moreover possible to envisage a single transduction stage, connectable in sequence to the outputs of the inertial sensors (or of the inertial sensor) by means of a multiplexer; in this case, the signals provided in sequence
20 by the transduction stage, corresponding to different preferential detection axes, can be temporarily stored in a register and then provided at a pre-determined instant to the comparison stage 16.

All of the above U.S. patents, U.S. patent application publications, U.S. patent applications, foreign patents, foreign patent applications and non-
25 patent publications referred to in this specification and/or listed in the Application Data Sheet, are incorporated herein by reference, in their entirety.

From the foregoing it will be appreciated that, although specific embodiments of the invention have been described herein for purposes of illustration, various modifications may be made without deviating from the spirit

and scope of the invention. Accordingly, the invention is not limited except as by the appended claims.